Appendix 2

Deuterons in TTB: Radiological Issues

I. Overview

Historically, deuterons have been excluded from transport in the Tandem to Booster (TTB) line because of the combination of the potential for relatively large neutron dose and relatively thin earth shielding. The relatively large dose occurs because the small binding energy of the deuteron allows its neutron to be "stripped." The berm thickness over the TTB tunnel is under 3 ft. in some places, but earth will be added to ensure a minimum thickness of 3.0 ft. prior to running with deuterons.

One of the controls important to safely transporting deuterons is that the energy will be limited to 12 MeV (6 MeV per nucleon). As discussed below, this means that activation of either soil or components is not an issue, so that the only real hazard is prompt radiation.

The scenario for transporting deuterons is given in Appendix 1 of this report. From that (deliberately conservative) scenario, the maximum point-like loss of deuterons is expected to be 4.5×10^{13} d in an hour and 2×10^{16} d in a year.

II. Prompt Radiation

Neutron penetration through the soil over the TTB has been estimated using the MCNPX code.[1] Although this code allows deuterons as incident particles, the physics model of d, nucleus interactions is more appropriate for incident energies of order 100 MeV and above. One manifestation of the incorrect model is that energy is not conserved when running the code with the 'default physics options.' A simple example is the reaction 56Fe (d,n) 57Co. This reaction has a Q of 3.7 MeV[2] which implies a maximum neutron energy for a 12 MeV incident deuteron of 15.7 MeV. Yet MCNPX gives a 'tail' of neutrons exceeding 25 MeV! An input option in MCNPX is available to force energy conservation, which biases the model.

Fig. 1 shows dose equivalent (hereafter called dose) at a distance of 1m from a very small target for the default version of the MCNPX code (but with a cut on neutron energy of 17 MeV), together with two measured points.[3] The code severely underestimates the dose at 90° in the case of the W target. Since 90° is the most relevant point for the transverse shielding problem the calculation for an Fe target will be used. However, fault studies are clearly important here since the best calculational tool available is clearly deficient.

Fig. 2 shows the maximum dose as function of depth in soil for both the default version of MCNPX and the version where energy conservation is enforced given an Fe target.[4] The line shown on Fig. 2 will be used to estimate dose.[5] This is $5.0\times10^{-16} \exp(-t/.511)$ with t in ft. For the minimum thickness t of 3.0 ft., the normal operating loss described in Appendix 1 gives about 64 μrem in an hour and 28 mrem in a year. An occupancy factor of 16 for the yearly dose gives a potential of less than 2 mrem for an individual. These estimates fall well within the definition of an uncontrolled area.

The initial fault studies are described in Appendix 5. The estimate above overestimates the fault study result by a factor of 1.9 at a depth of 2.69 and a factor of 5.5 at a depth of 3.61 ft. If one divides the 3.0 ft. soil estimates immediately above by 1.9 the results become 34 μrem in an hour and 15 mrem in a year.

III. Activation

As mentioned in Section I above, activation is not expected to be a problem because of the very low energy. A table of Q values for (primarily) n and 2n reactions is given in Table 1.[6]

Table 1

Q-Values for neutron producing reactions d,n and d,2n on Fe, Ta, W and D, and for the 22Na and tritium producing reaction 28Si (n, αt) 22Na

Target	Reaction	Product	Q(MeV)
54Fe	d, n	55 Co	2.74
54Fe	d,2n	54Co	-11.34
56Fe	d, n	57 Co	3.71
56FE	d, 2n	56 Co	-7.67
57Fe	d, n	58 Co	4.63
57Fe	d, 2n	57 Co	-3.94
181Ta	d, n	182 W	4.77
181Ta	d, 2n	181 W	-3.29
182W	d, n	183 Re	2.53
182W	d, 2n	182 Re	-5.90
183W	d, n	184 Re	2.82
183W	d, 2n	183 Re	-3.65
184W	d, n	185 Re	3.09
184W	d, 2n	184 Re	-5.59
186W	d, n	187 Re	3.68
186W	d, 2n	186 Re	-3.69
2H	d,n	3He	3.06
28Si	n,αt	22Na	-25.6

The highest neutron energy from any n or 2n reaction with any of the possible targets in the TTB line (Fe,Ta,W) is 12 + 4.77 MeV ≈ 17 MeV. The last entry in Table 1 gives the 'proto-typical' activation reaction in soil, as it produces both 22Na and 3H, which are the only two radioisotopes of interest since they live long enough to migrate to the water table by leaching. As shown, it lacks about 9 MeV of being possible from an n or 2n reaction, which dominate the inelastic cross section.

Multi-fragment reactions from the higher atomic weight targets do give the kinematic possibility of higher energy neutrons. For example, the reaction d + 181Ta $\rightarrow$ 16O + 166Dy +n has a Q value of about 23 MeV. In principal, such a reaction would cause both component activation (166 Dy emitting photons with an 82 hr. half life) and soil activation from the high energy neutron. However, the cross section for this reaction is probably extremely small, and the 35 MeV of available kinetic energy is divided among the reaction products. In uranium fission, for example, the neutron energy spectrum peaks at about 15 MeV of 200 MeV available.

In summary, it is expected that any activation in soil will be exceedingly small, probably not measurable. Since it is very difficult to accurately estimate very small quantities, the next gives an upper limit for such activation. The following two sections give estimates for component and air activation.

(A) Upper Limit on Soil Activation

As mentioned above, the default version of MCNPX gives a non-physical 'tail' of high energy neutrons. The maximum flux of neutrons > 20 MeV on the wall of the tunnel turns out to be 1.22×10^{-10} n/cm^2-d. At *30* MeV, the MCNPX code gives .03 tritons per interaction in soil. Suppose one 22Na atom is formed for each triton by the reaction in the last row of Table 1. An extreme upper limit is obtained by blindly applying the non-existent > 20 MeV flux with the 30 MeV cross section to get 1.22×10^{-13} 22Na atoms per cc per d on target.

In a model of groundwater contamination developed by Ed Lessard, and described in the AGS SAD, 3×10^9 22Na atoms/cc(soil)-yr. (1.5×10^{11} 'CASIM stars' per yr.) corresponds to 5×10^4 pCi/l (water) at the water table. Current BNL policy requires mitigation whenever the estimate of groundwater activation in the context of this model exceeds 5% of the drinking water standard, or 20 pCi/l. The 20 pCi/l corresponds to 1.2×10^6 22Na atoms/cc-yr. Using the extreme limit of 1.22×10^{-13} 22Na atoms per cc per d on target above requires ~ 10^{19} d at a point in a year in comparison to the 2×10^{16} per year estimated in Appendix 1. *An upper limit of about 10^{-4} of the drinking water standard* clearly indicates that soil activation is not a problem.

(B) Component Activation

Component activation can arise in principle from two sources. The smallest of these is activation resulting from the produced neutrons. An upper limit for this source was made by utilizing the 'Danger Parameters' described by Barbier[7] and extensively discussed elsewhere[8] together with the unphysical assumption that 1% of the neutron spectrum would be above the typical activation threshold. This upper limit estimate, which is not discussed further here, is very small, about 20 nanorem per hour for an exposure of 10 namps. DC equivalent on an Fe object for a full day.

Of more interest is activation resulting from the deuteron beam itself as illustrated most clearly by the reactions in Table 1 above. Unfortunately, the cross sections for these are not known. An estimate is made here which is intended to be very conservative. Again, the activity estimated will assume 10 namps. DC equivalent on an Fe object for a full day.[9] Suppose that all the neutrons per stopping d given by MCNPX (9.98×10^{-4}) in Fe come from the single n reactions in Table 1. The activity at 0 cooling time is then simply the sum over the cobalt isotopes given by the activation formula, and the induced activity at 1 ft after 24 hours irradiation is given by:

$$\text{Production Rate} \times Const \times \sum_i f_i (1 - \exp(-t/\tau_i) \times k_i$$

where *i* sums over the 3 isotopes of cobalt,[10] f_i the fraction of parent Fe isotope, τ_i the mean life, and k_i the k_γ factor for isotope i. The k_γ factor gives rad per hour in tissue at 1m distance per Curie. The value of Const is therefore $10/3.7 \times 10^{10}$ where the factor of 10 in the numerator just converts to dose at 1m to dose at 1 ft. For the reaction rate assumed (6.25×10^{10} d/sec times 9.98×10^{-4}) the result is about 0.6 mrad/hr.

Now, on qualitative grounds, the original assumption must be extremely conservative. The model of (d,p) reactions is as follows. The neutron and proton in the incoming deuteron are loosely bound and the charge of the target nucleus polarizes the deuteron. Then the neutron enters the nucleus and the proton is simply repelled by the Coulomb field. Similarly for the (d,n) reactions of Table 1, the proton enters the nucleus. However, at this low energy, the proton 'cannot' overcome the Coulomb barrier. Since the meaning of 'cannot' is rarely more than a factor of 10, **the best estimate for the exposure considered is that the activity is likely to be in the tens of microrem per hour at 1 ft. distance**.

Since the exposure estimated is extreme,[9] an actual activity of, say, 50 μrem/hr is unlikely. However, such activation would not create a problem since the activated material is contained within the beam pipe, and all personnel at the Tandem facility are trained radiation workers. **The conclusion of this section is simply that care should be taken to perform radiation surveys following the initial running periods with deuterons.**

(C) Air Activation

Most of the radionuclides normally considered in air activation estimates are highly suppressed at these very low energy. As an example, one of the most likely reactions normally considered, 16O (n,2n) 15O, has a Q of -15.7 MeV. However, one well-known component of air activation will exist relatively copiously, namely the creation of 41A from the 0.93% of A in air by thermal neutrons.

The estimate here parallels that of the BAF SAD. An estimate is made of the number of 41A atoms per cc per year in the TTB tunnel from:

$$\varphi \times \sigma \times N_P$$

where φ is the thermal neutron flux, σ the (large) capture cross section of 630 mb., and N_P the 'parent' 40A concentration in air. The last quantity is calculated to be 4.62×10^{17} atoms/cc.[11]

The thermal neutron flux[12] was determined by another MCNPX calculation (with an Fe target) in a geometry to that which generated Fig. 2. In this case earth surrounding a 4 ft. radius tunnel degrades the neutron energy spectrum. The flux was sampled at various places in the tunnel interior. As in previous similar estimates, the flux was found to vary very little with position, and in this case had an approximately constant value of 1.5×10^{-9} n/cm^2-d. For the 2×10^{16} stopping d in a year at a point this converts to 3×10^{7} n/cm^2-yr. The final result is 0.873 41A atoms/cc-yr. or an activity concentration of 2.5×10^{-15} Ci/cc-yr. This is 4 orders of magnitude smaller than the estimate in the BAF SAD.

IV. Faults

As described elsewhere in this document, two chipmunks will continuously monitor the beam current. The maximum current desired for Booster and AGS tuning is 100 na. DC equivalent. The chipmunks will be set to alarm at 120 na. and will shut off the Tandem at 200 na. The worst fault would then be a scenario where slightly under 200 na. would exist simultaneously with an unnoticed valve closure (say) and an unnoticed alarm. If this situation would exist for an hour adjacent to one of the minimal berm thicknesses of 3.0 ft. of earth, the MCNPX estimate corrected downward by the 1.9 factor from the fault study result, as discussed above, would give 3.3 mrem. It would take 7 plus such occurrences in a year to reach the 25 mrem per year limit even without taking occupancy into account. This is not considered credible.

V. Quality Factor

The MCNPX code gives all its results as a function of neutron energy, which allows an estimate of the quality factor.[13] For neutrons in the tunnel coming directly from the target (Fig. 1) the estimated QF is about 8. For neutrons having penetrated 3 ft. of soil, in the geometry of Fig. 2, the QF is estimated to be 2.5.

References/Footnotes

1. L. S. Waters, Ed., “MCNPX User’s Manual, Version 2.1.5”, November, 1999. See also H.G. Hughes, R.E. Prael, R.C. Little, “MCNPX – The LAHET/MCNP Code Merger,” X-Division Research Note, April, 1997. MCNPX has various physics options; only the default options were used.

2. In this section Q is defined as the incident state rest masses minus the final state rest masses.

3. P. Thieberger, Minutes of C-AD Radiation Safety Committee Meeting of July 3, 2001.

4. The calculation was done in a cylindrical tunnel geometry where the tunnel radius is 81.3 cm. (32 in.), which is the distance of closest approach of soil to the actual tunnel. The definition of 'soil' is a substance with atomic composition of .084H, .611O, .305Si having a density of 1.9 g/cc.

5. The line is below the default MCNPX estimate by the same amount as the measured data is below the 90 point in Fig. 1. Again, measured data is critical for accuracy in this "ill-explored" regime.

6. Table 1 courtesy of P. Thieberger.

7. M. Barbier, "Induced Radioactivity," John Wiley & Sons, Inc., New York, 1969.

8. A.J. Stevens, "Estimating Induced Activity Using 'Danger Parameters'," C-AD ES&F Division Tech Note 158, 2001.

9. For the heavier targets, similar estimates are lower by an order of magnitude or more. There is no intention to expose Fe for any period of time, and the heavier targets are exposed for minutes at a time during tuning.

10. Actually 58Co is an isomer, both states of which are assumed equally populated. 54Co dominates the result.

11. The density of air is assumed to be .0012 g/cc, and the composition as follows: 78.08% N_2, 20.95% O_2, 0.03% CO_2, and 0.93% A.

12. "Thermal" is defined here as less that 1 ev.

13. The Quality Factor vs. neutron energy is taken from ICRU Report No. 20 (ICRU, 1971b).

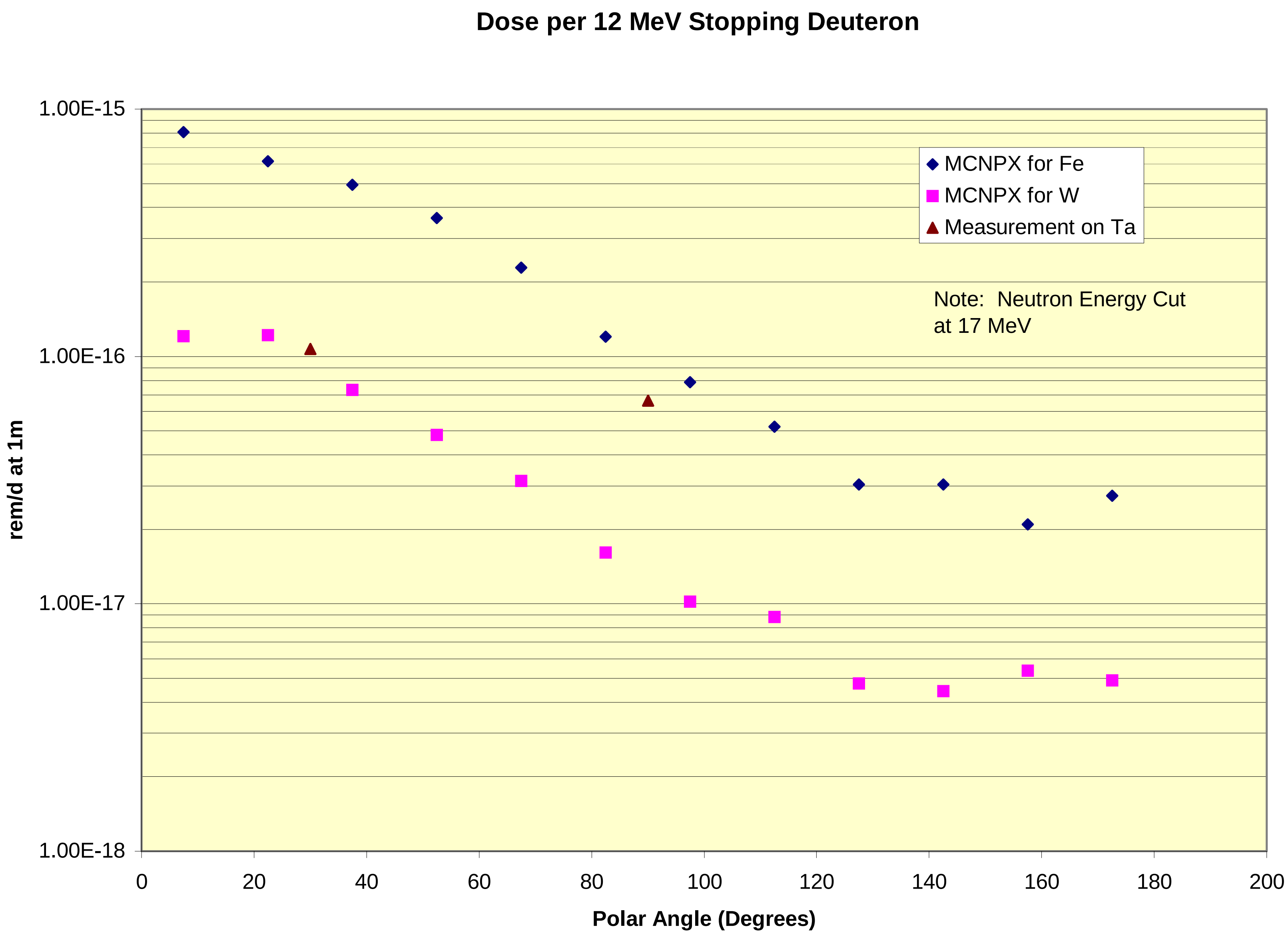

Fig. 1 MCNPX Estimates Compared to Measured Data

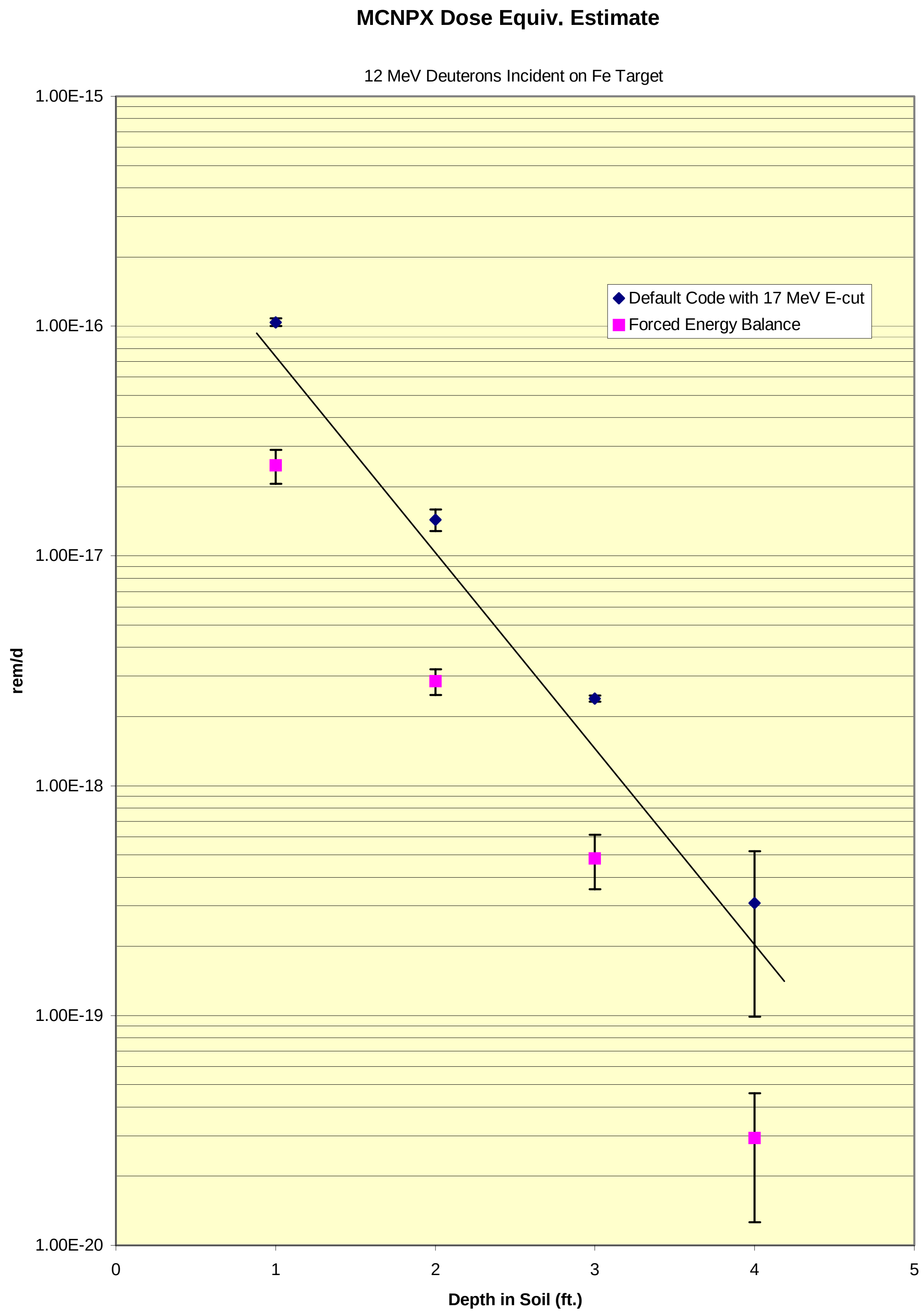

Fig. 2 MCNPX Estimates vs. Depth in Soil